Manuscript Details

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Title	Ductility and overstrength of nailed CLT hold-down connections
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Abstract

The structural performance of nailed hold-down connection systems used for cross-laminated timber (CLT) shear walls under monotonic and cyclic loading was experimentally evaluated. Critical connection performance parameters, including strength, stiffness, ductility, and overstrength, were derived from the testing of 68 hold-down connection specimens. The nailed CLT hold-down connections achieved moderate to high ductility when fracture failures of their metal brackets were avoided. The hold-down connection systems with 3 mm thick commercial brackets achieved ductility factors ranged from 2.7 to 4.3, while the hold-down connection systems composed of 10 mm thick steel plates and longer nails achieved larger ductility factors which ranged from 4.7 to 6.3. The overstrength factors of the hold-down systems ranged from 1.45 to 1.62 except the one composed of the 10 mm thick brackets and 100 mm long nails installed at wide spacing. It was also found that the yield strength of the nailed hold-down connections under monotonic loading was similar to that obtained by cyclic loading.

Keywords	cross-laminated timber (CLT); nailed connections; hold-down connections; ductility; overstrength
Taxonomy	Earthquake Safety Design, Earthquake Engineering
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Submission Files Included in this PDF

File Name [File Type]

Cover leter20200411-LM.docx [Cover Letter]

Response to reviewers20200411-LM.docx [Response to Reviewers]

Highlights.docx [Highlights]

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declaration-of-competing-interests.docx [Conflict of Interest]

Author statement.docx [Author Statement]

Dear Editor,

We are sending you our revised manuscript entitled "Ductility and overstrength of nailed CLT hold-down connections" by W. Dong et al. on 13th April, 2020. We have revised the paper to address the reviewers' comments as much as possible.

The modifications that we have made are listed below. The adjustments that we conducted to address the reviewers' comments are printed in **bold**. The reviewers can also find the details and explanations in the attached document "Response to reviewers".

1. Highlight was modified to 5 bullet points (**Comment i from reviewer 2**)
2. Line 1-3, formatted the title font size and author names.
3. Line 6-19, abstract has been modified for better presentation and the format was adjusted to "justify". (**Comments from reviewer 1 and comment ii from reviewer 2**)
4. Line 23, aligned the section title to the left for better format configuration. The same modifications have been made for other section titles.
5. Line 24, left indentation was added to make the paragraph easier to read. The same modifications have been made for other paragraphs.
6. Line 45, "angel" to "angle" (**Comment iii from reviewer 2**)
7. Line 94-106, some information was combined to make the writing structure clearer but all technical contents keeps the same with previous version.
8. Line 98, "10 mm-thick" to "10 mm thick" for consistency. The same modifications have been made for rest of terms.
9. Line 107-112, information about timber properties was repositioned as well as Table 2.
10. Line 112, deleted "MOE". (**Comment iv from reviewer 2**)
11. Line 114, centred the caption of Table 1. The same modifications have been made for all other tables. (**Comment ii from reviewer 2**)
12. Line 115, added "1" for the note and reduce the font size to 9 to distinguish the table note with main contents. The same modifications have been made for other notes. (**Comment iv from reviewer 2**)
13. Line 121, adjusted the location of Table 2 to make it on one page. The same modifications have been made for all other tables except Table 4. (**Comment ii from reviewer 2**)
14. Line 124-128, reduced some contents to make the paper more brief.
15. Line 131, centred the caption of Figure 1. The same modifications have been made for all other figures. (**Comment ii from reviewer 2**)
16. Line 134-155, reduced some contents to improve the presentation.
17. Line 152, "that" to "those".
18. Line 174, modified the caption of Figure 3 for better presentation. The same modifications have been made for other similar subfigures.
19. Line 176-181, recalled the replicates in Table 1 and added the monotonic loading information (**Comment v from reviewer 2**)
20. Line 176-185, the information was reorganized to be more brief.
21. Line 186, replaced Figure 4 with a better quality picture.
22. Line 188, the contents in Section 3 keeps the same but some sentences were rewritten for better presentation.
23. Line 235-240, only showed all curve for one sub-type and then for rest of sub type, one monotonic and one cyclic curve were provided instead. (**comment vi from reviewer 2**)
24. Line 244-245, mentioned the criteria for analysis to make the results more objective. All analysis in the rest of the paper follows the criteria. (**Comment vii from reviewer 2**)
25. Line 252-255, explained each case of the equation (3). (**Comment iv from reviewer 2**)
26. Line 274-283, redrew all curves to make them clear. (**Comments from reviewer 1 and comment vi from reviewer 2**)

27. Line 290-291, deleted the difference of 9% because they were similar. All difference within 10% now are considered to be similar. The same modifications have been made for rest of the analysis. (**Comment vii from reviewer 2**)
28. Line 306-309 and Line 319-322, added more discussion about overstrength value.
29. Line 320-325, modified the discussion about timber species to be more objective. (**Comment vii from reviewer 2**)
30. Line 377-391, added more conclusions that matched the objectives mentioned in the abstract and introduction. (**Comment viii and ix from reviewer 2**)
31. Line 382-385, clarified the conclusion about two timber species to be more objective. (**Comment vii from reviewer 2**)
32. Line 393, "Acknowledgement" to "Acknowledgements"

Please let us know if you have any further questions.

Best regards,

Wenchen Dong

General responses to all reviewers

The authors really appreciate the valuable feedback from all the reviewers. In the revised manuscript, we tried our best to address the questions/comments raised by the reviewers and to improve the overall readability.

-Reviewer 1

- The paper is short with low quality of writing and presentation. Organization of the manuscript is NOT appropriate. Figures and graphs are presenting in a poor quality.

Reply: Thank you for your time and comments. We have made revisions to improve the overall writing and presentation. But all technical contents and conclusions remain the same as what was presented in the original submission. Specifically, we have modified curves and figures with higher resolution. This paper investigates the influence of hold-down design parameters including nailing patterns, nail length, timber species, and hold-down bracket types on the nailed CLT hold-down connection performance. The authors believe that this work complements previous experimental database on CLT connections and provides insightful information for engineers to carry out robust seismic design of CLT shear walls following capacity design approach.

-Reviewer 2

- The manuscript presents an experimental investigation on the monotonic and cyclic behavior of nailed hold-down connections in cross laminated timber elements. The manuscript is overall well written, in a good and clear English, and the topic in investigation is interesting and up-to-date. This Reviewer recommends the manuscript being accepted for publication after the following issues are addressed in the revised version:

(i) The third bullet of the highlights seems rather long (more than the 85 permitted characters). Please separate this into two as a maximum of five bullets is usually allowed;

Reply: Addressed. The highlights have been divided into 5 bullets to meet the requirements.

(ii) Though the manuscript is still to be formatted into its final (journal) form, this Reviewer would have like to have seen more care taken into the presentation of the manuscript. The authors should bare in mind that a first good impression is always in their favor. For instance, tables and figures and/or their captions are not centered, there are tables and figures separated in two pages without any need for it, the abstract is not justified (aligned left instead), etc…;

Reply: Addressed. The authors have adjusted all formats. All tables and figures and their captions are now centred. Most tables have been adjusted to make sure they are on the same page except Table 4 because it is too long to put on one page. All figures have been kept on one page and the abstract has been justified as well.

(iii) Also taking into account the previous comment, please revise the text once more as some typos were found (e.g., line 45: 'angel' -> 'angle' and line 116: 'have -> 'has');

Reply: Addressed. All spellings have been checked again.

(iv) The use of 'MOE' for modulus of elasticity is rather odd. Please use 'E' as its symbol or don't use any as there are not a lot of references to this property. Please briefly explain each case that appears in equation (3). The correspondence for Note '1' in Table 1 was not found;

Reply: Addressed. Reference to MOE has been deleted as suggested. Equation (3) is explained in line 252-255 in the revised version. "The three equations presented three possible failure modes: failure solely by embedment in the timber, failure by a combination of embedment in the timber and single yielding in the fastener and failure by a combination of embedment in the timber and double yielding in the fastener." The cardinal "1" was added in Table 1 (line 115).

(v) When presenting Figures 9 to 11 and Tables 4 to 6 (lines 239 to 244) the authors should recall the reader that 3 to 5 repetitions of each test were conducted, as this information is basically only in the test matrix but not very clear in the text;

Reply: Addressed. The number of replicates is now emphasized in line 176-178 when explaining table 1. "As shown in Table 1, five replicates of each hold-down sub-type were tested under each monotonic and cyclic loading condition, except Type B-"P1"-ø4×60 and Type C sub-types which had three replicates tested under each loading type."

(vi) Also, curves in Figures 9 to 11 have a very poor formatting (almost straight out of the excel sheet) and are close to being unreadable. It is imperative that these are improved. This Reviewer has the opinion that it is irrelevant and counter-producing to present every curve. One curve per case (i.e., one monotonic and one cyclic in each graph) is more than enough to illustrate the behaviors – choose, for instance, the curves that correspond to the 'average' behavior for each case. State this in the text (that one curve per test is shown to illustrate the behavior of a given connection). Then, in Tables 4 to 6, all the results may/should be shown (as the authors do);

Reply: Addressed. The authors now show all curves for only one sub-type in the revised version and have chosen one representative monotonic and one representative cyclic curve for the rest sub-types as suggested by the reviewer. The curves have been updated with higher resolution in line 274-283. An explanation has been added in line 235-240: "As an example, Figure 9 shows the monotonic and cyclic load-slip curves of all specimens in Type A-"F"-ø4x60. It was found that the curves in each hold-down sub-type were consistent. Therefore, for each hold-down sub-type, one representative monotonic load-slip curve and one representative cyclic load-slip curve are provided in Figures 10 to 12. In general, the backbones of the cyclic curves matched well against the monotonic curves."

(vii) The authors need to be more objective in their analysis of the results. For instance, in lines 294 to 296 they claim that 'The change of the nailing pattern did not have an influence on the yield strength (50.5 kN vs. 50.7 kN), but the average μ was reduced from 3.1 to 2.7.' But then in lines 306 to 307, 'The average μ and yield strength was similar (2.9 vs. 3.1 and 49.6 kN vs. 50.7 kN)'. In both cases the differences are of similar magnitude, near 10% but classified differently (similar, reduced) in magnitude. Some variability of the test results must always be accounted for;

Reply: Addressed. Thanks for this valuable comment. The authors have now emphasized the analysis criteria in line 242-245 in the revised version. "The variability in each sub-type was primarily due to the inherent variability of wood including inconsistent density, moisture contents, grain direction, natural defects, etc. In term of that, test results within 10% difference are considered to be similar on the following analysis." This means that the authors would consider all results within 10% difference as similar results and mention all differences that were more than 10%. "The average μ and yield strength was similar (2.9 vs. 3.1 and 49.6 kN vs. 50.7 kN)" has been kept in line 313-314, but the "The change of the nailing pattern did not have an influence on the yield strength (50.5 kN vs. 50.7 kN), but the average μ was reduced from 3.1 to 2.7" has been modified in line 307-308 by mentioning the percentage of difference. Similar changes have been made for line 290-292 and line 316-319 to make the analysis more objective.

(viii) The sentence (or similar) 'Therefore, for these connection types, monotonic tests may be used to provide good predictions for yield strength and conservative predictions for the ductility factor under cyclic loading' should also be in the conclusions. It is considered relevant and of

practical interest for the technical-scientific community. The 'connection types' should be called by their names and the degree (factor, value…) of 'conservative predictions' of the ductility factor should be given;

Reply: Addressed. This sentence has been modified and been added into the conclusion (line 386-391). The authors have done more detailed comparison in line 350-358. Instead of showing 15% for all specimens, the authors decided to provided a range to give a clear statement on different hold-downs. "Except for Type C-"T"-ø4x100, the hold-down average yield strength obtained from the monotonic tests was similar to the one obtained from cyclic tests. For Type C hold-down connections, the ductility from the monotonic tests was similar to the one obtained from cyclic tests as well. However, for Type A and B hold-down connections, the average cyclic ductility was higher than the monotonic ductility by a range of 16% to 38% except Type A-"P2"-ø4x50."

(ix) A general conclusion on the contribution of the work for one of the main objectives/aims stated must be included. Objective/aim: 'Therefore, it is often the designer's responsibility to assume overstrength factors using rational engineering judgment. This often leads to either unsafe or uneconomical design. So far, very limited studies have been conducted to establish overstrength factors for some timber connection types …'.

Reply: Addressed. The objective of this paper is to investigate the influence of different design parameters and provide insight on the ductility and overstrength that engineers can use for the commercial hold-down connections and the customized hold-down connections. We have reported overstrength values and ductility values in the conclusions of the revised version. In addition, the influence of all parameters has been added in the conclusions (line 377-391).

-Reviewer 3

Great work and test campaign, different aspects have been investigated and different comparisons made giving clear and reliable outcomes. Nothing to point out or that I think should be corrected.

Reply: Thanks for your time on reviewing this paper. A number of revisions have been made to improve the writing and presentation of the paper without changing the technical contents and main conclusions.

Highlights

- Sixty-eight nailed CLT hold-down connections were tested.
- Overstrength and ductility factor of connections were provided.
- Influence of nailing patterns and nail length was discussed.
- Two widely used timber species in New Zealand were used.
- Two different hold-down bracket types were employed.

Ductility and overstrength of nailed CLT hold-down connections

Wenchen Dong, Minghao Li, Lisa-Mareike Ottenhaus, and Hyungsuk Lim

Abstract

The structural performance of nailed hold-down connection systems used for cross-laminated timber (CLT) shear walls under monotonic and cyclic loading was experimentally evaluated. Critical connection performance parameters, including strength, stiffness, ductility, and overstrength, were derived from the testing of 68 hold-down connection specimens. The nailed CLT hold-down connections achieved moderate to high ductility when fracture failures of their metal brackets were avoided. The hold-down connection systems with 3 mm thick commercial brackets achieved ductility factors ranged from 2.7 to 4.3, while the hold-down connection systems composed of 10 mm thick steel plates and longer nails achieved larger ductility factors which ranged from 4.7 to 6.3. The overstrength factors of the hold-down systems ranged from 1.45 to 1.62 except the one composed of the 10 mm thick brackets and 100 mm long nails installed at wide spacing. It was also found that the yield strength of the nailed hold-down connections under monotonic loading was similar to that obtained by cyclic loading.

Keywords: cross-laminated timber (CLT), nailed connections, hold-down connections, ductility, overstrength

1. Introduction

Nails are commonly used mechanical fasteners in residential timber buildings including light timber-framed buildings in North America and post-and-beam timber buildings in Japan (Li and Lam, 2009). Extensive research has been conducted on evaluating and predicting the performance of nailed timber joints used in light-frame construction (Li et al. 2012, Lim et al. 2017). In mass timber construction, nails can be used to connect panelised members such as cross-laminated timber (CLT) and other structural components in combinations with splines, plates or brackets according to the CLT Handbook (Karacabeyli and Douglas, 2013). As CLT has become a popular option in mass timber construction in recent years (Brandner et al. 2016), numerous studies have been conducted to assess the structural performance of various connection types used in CLT structures, including panel-to-panel (Hossain et al. 2016), wall-to-panel (Gavric et al. 2015a), and wall-to-foundation connections (Gavric et al. 2015b).

Wall-to-foundation anchoring connection systems have critical contributions to lateral resistance of CLT structures under wind or seismic loads (Ceccotti et al. 2013). Despite the development of high-performance anchoring systems such as X-RAD (Polastri et al. 2017), utilization of nails along with steel brackets for hold-down connections and shear keys is still a common practice and has been actively researched. Steel angle brackets are widely used as shear keys in CLT shear walls. Research has confirmed that they can provide both shear and uplifting resistance (Gavric et al. 2015b) and their performance is governed by geometries of the brackets and assembly parameters such as nail length (Tomasi and Smith, 2015). The complicated behaviour of the angle bracket connections has also been studied by numerical simulations. For example, a finite-element based model was developed to simulate angle bracket connections under combined axial-shear loading conditions (Schneider et al. 2014), and was further validated against destructive test results of a different angle bracket type subjected to the same loading condition (Pozza et al. 2017, Pozza et al. 2018). Nailed hold-down connections are commonly used to provide uplifting restraints for CLT shear walls. Their performance has a direct relationship with the number and the type of nails used to connect the hold-down brackets to CLT panels. Ductile failure characterized by yielding of nails was observed when hold-down connections had nail quantities less than half the number of the pre-drilled holes on the commercial brackets (Flatscher et al. 2015, Benedetti et al. 2019). However, the effect of nailing pattern on failure mechanisms of hold-down connection systems has not been researched.

Capacity design is often used in seismic design of timber buildings. Timber members are protected from premature brittle failure by applying overstrength factors derived from the ductile components to the design demand of the members. This ensures that the ductile elements are the weakest components along the load path. For timber buildings, these ductile components are typically well-detailed connections with metal dowel-type fasteners. In order to achieve robust seismic design for CLT shear walls, ductility and overstrength properties of ductile components such as hold-down connections need to be well understood. However, ductility and overstrength properties of timber connections are hard to predict and often requires experimental testing. Equation (1) is commonly used to define the connection/system ductility factor μ.

$$\mu = \frac{\Delta_u}{\Delta_y} \tag{1}$$

where Δ_u = ultimate displacement corresponding to the post-peak deformation at 80% of the maximum load; Δ_y = displacement at yield point.

The discrepancy between analytically calculated design strength in code provisions and the 95th-percentile of the true strength distribution is generally referred as overstrength. Jorissen and Fragiacomo (2011) defined the overstrength factor for timber connections γ_{Rd}:

$$\gamma_{Rd} = \gamma_M \cdot \gamma_{an} \cdot \gamma_{0.95} = \frac{F_k}{F_d} \cdot \frac{F_{0.05}}{F_k} \cdot \frac{F_{0.95}}{F_{0.05}} \tag{2}$$

where γ_M = overstrength attributed to material safety factor; γ_{an} = overstrength attributed to conservatism of analytical models; $\gamma_{0.95}$ = overstrength attributed to difference between 5th and 95th percentile of strength distribution; F_k = characteristic strength; F_d = design strength; $F_{0.05}$ = 5th percentile of strength distribution; $F_{0.95}$ = 95th percentile of strength distribution.

Most timber design standards do not provide overstrength factors of ductile connections for capacity design. One rare example is the New Zealand timber standard NZS 3603 (1993) that explicitly stipulates a connection overstrength factor of 2.0 for nailed connections in plywood shear walls. Therefore, it is often the designer's responsibility to assume overstrength factors using rational engineering judgment. This often leads to either unsafe or uneconomical design. So far, very limited studies have been conducted to establish overstrength factors for some timber connection types (Gavric et al. 2015b, Brühl et al. 2014, Ottenhaus et al. 2018a, Ottenhaus et al. 2018b).

This study is to assess the structural performance of commonly used nailed hold-down connections in CLT. Influence of hold-down design parameters including nailing patterns, nail length, timber species, and hold-down bracket types on the hold-down connection performance including ductility and overstrength is investigated. The test results will provide insightful information for robust seismic design of CLT shear walls following the capacity design approach.

2. Materials and Test Methods

2.1 Connection specimens

Table 1 lists the test matrix of the hold-down connections. A total of 68 connection specimens were constructed for three types of hold-down connections using two bracket types and two wood species. Commercial WHT440 hold-down brackets (Rothoblaas, 2019) were installed on either Douglas-fir (DF) or Radiata pine (RP) CLT, while 10 mm thick steel plates were only installed on RP CLT. WHT440 bracket is one of the common hold-down brackets used in CLT construction to provide overturning restraints to shear walls under lateral loads; it is composed of 3 mm thick steel plates with thirty ø5 mm holes. Within each hold-down type, sub-types were defined to include five nailing patterns and three nail sizes as experimental design factors. For example, Type A-"F"-ø4×60 sub-type represents Type A hold-down connections with ø4×60 nails in a full nailing pattern "F". Similarly, Type C-"W"-ø4×100 sub-type represents Type C hold-down connections with ø4×100 nails in a nailing pattern "W" indicating wide nail spacing.

Table 2 lists the properties of the CLT materials in terms of species, layups, timber grades, densities, and moisture contents. The characteristic densities were calculated according to EN 14358 (2016). These characteristic densities were used in the calculation of the characteristic strength of the hold-down connections. The lamination grade was SG8, the most commonly used timber grade in New Zealand with an average Modulus of Elasticity of 8 GPa.

Table 1 Test matrix

Hold-down type	**Sub-type**	**Timber species**	**Bracket type**	**Nail size**	**Nail quantity**	**Nailing pattern[1]**	**No. of replicates**	
							Mono.	Cyc.
Type A	Type A-"F"-ø4×60	Douglas-fir (DF)	WHT440	ø4×60	30	F	5	5
	Type A-"P1"-ø4×60			ø4×60	15	P1	5	5
	Type A-"P1"-ø4×50			ø4×50	15	P1	5	5
	Type A-"P2"-ø4×50			ø4×50	15	P2	5	5
Type B	Type B-"P1"-ø4×50	Radiata pine (RP)	WHT440	ø4×50	15	P1	5	5
	Type B-"P1"-ø4×60			ø4×60	15	P1	3	3
Type C	Type C-"W"-ø4×100	Radiata pine (RP)	10 mm thick steel plate	ø4×100	15	Wide spacing	3	3
	Type C-"T"-ø4×100			ø4×100	15	Tight spacing	3	3

Note: 1. nailing patterns are shown in Figure 1 and Figure 2.

Table 2 Summary of CLT properties

Hold-down type	**Timber species**	**CLT layup**	**Timber grade**	**Density (kg/m³)**		**Moisture content**
				ρ_{mean}	ρ_k	mean
Type A	Douglas-fir (DF)	35/35/35	SG8	467	421	10.9%
Type B	Radiata pine (RP)	35/35/35	SG8	469	434	10.8%
Type C	Radiata pine (RP)	35/20/20/20/35	SG8	474	450	9.9%

Type A hold-down connections

WHT440 brackets were mounted on 3-ply DF CLT segments with a layup of 35 mm/35 mm/35 mm using either ø4×50 or ø4×60 nails recommended by the bracket manufacturer (Rothoblaas, 2018). The nails were driven through the holes of the brackets following the patterns illustrated in Figure 1: full nailing ("F") and two partial nailing ("P1" and "P2") patterns.

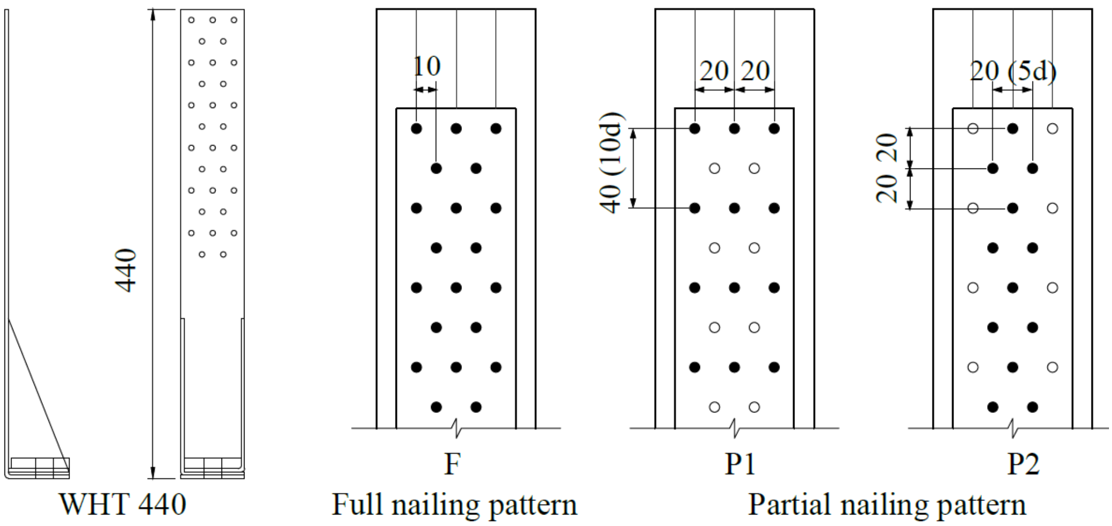


Figure 1 WHT440 bracket and nailing patterns in Type A and Type B hold-down connections

Type B hold-down connections

WHT440 brackets were installed on 3-ply RP CLT segments with a layup of 35 mm/35 mm/35 mm using fifteen of either ø4×50 or ø4×60 nails. Only the partial nailing pattern "P1" shown in Figure 1 was adopted in assembling Type B hold-down specimens to study the influence of the wood species on the connection performance.

Type C hold-down connections

10 mm thick steel side plates with predrilled ø5 mm holes were installed on 5-ply RP CLT with a layup of 35 mm/20 mm/20 mm/20 mm/35 mm using fifteen ø4×100 nails. The side plates were made of Grade 300 steel with the specified yield strength of 300 MPa according to the standard AS/NZS 4671 (2001). One reason to use thicker steel plates was to avoid fracture failure of the hold-down brackets observed in the experimental study conducted by Gavric (2015b). The longer ø4×100 nails were used to ensure sufficient nail embedment length and avoid early-stage nail withdrawal. Two different nailing patterns (tight and wide) described in Figure 2 and Table 3 were adopted. The tight nailing pattern primarily followed the new draft of New Zealand timber design standard NZS/AS1720.1 (2019). In typical configurations of nailed hold-down connections installed on CLT walls, a_3 is more than 5d as there is sufficient spacing between the nail groups and the wall bases. Therefore, a_3=8d was used for Type C hold-down connections. In the wide nailing pattern, the row spacing, a_1, and the fastener spacing within the rows, a_2, were doubled from those of the tight nailing pattern. The purpose of choosing different nail spacing was to study whether brittle failure in wood, such as group tear-out or wood splitting, would occur and how it would affect the hold-down connection behaviour.

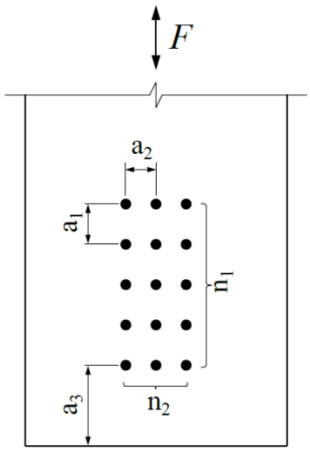


Figure 2 Definitions of nail spacing parameters in Type C hold-down connections

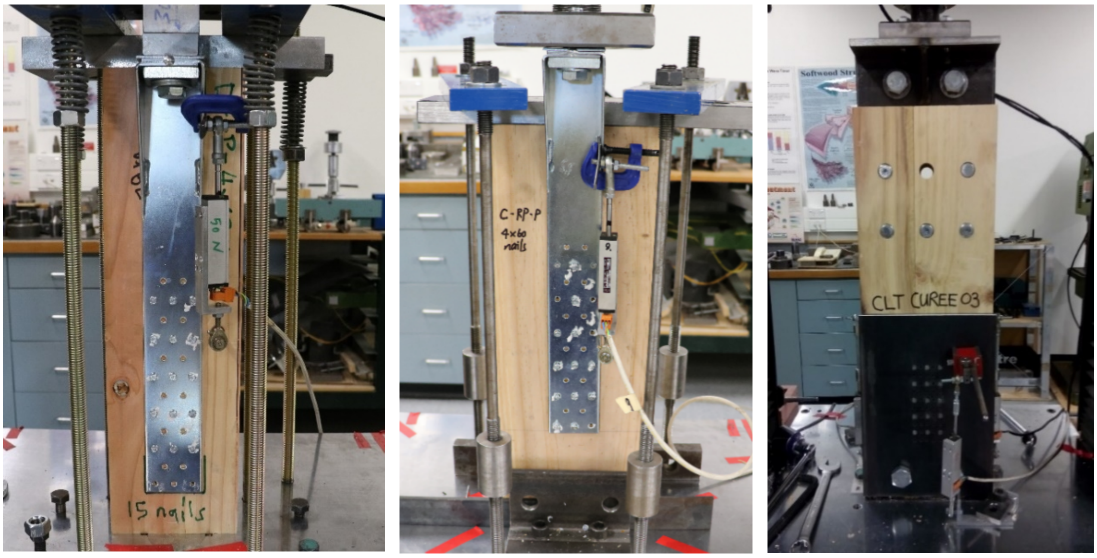
Table 3 Nail spacing in Type C hold-down connections

Layout	Wide spacing (mm)	Tight spacing (mm)	NZS/AS 1720.1 (mm)
a_1	32 (8d)	16 (4d)	16 (4d)
a_2	24 (6d)	12 (3d)	12 (3d)
a_3	32 (8d)	32 (8d)	20 (5d)
n_1	5	5	
n_2	3	3	

Note: symbols in parentheses denote the spacing in ratios of fastener diameter

2.2 Test methods

Figure 3 shows the test setups of the three hold-down types. For Type A and Type B hold-down connections, CLT blocks were restrained by steel rods and steel plates in place, while the load was applied by an actuator connected to the hold-down bracket via a ø16 mm anchoring bolt. One potentiometer was mounted onto the specimens to measure the relative displacement/slip between the hold-down bracket and the CLT along the vertical loading direction. For each Type C hold-down, the actuator was connected to the CLT block with a 20 mm thick inserted steel plate and five ø25 mm steel dowels reinforced by self-tapping screws. The top connection was overdesigned to provide significantly higher strength and stiffness than the Type C hold-down connection that was loaded to failure. The end with the 10 mm thick steel side plates was fixed to the test table. One potentiometer was also mounted on each Type C specimen to measure the relative displacement between the steel plates and the CLT along the loading direction.



(a) (b) (c)

Figure 3 Experimental setups for (a) Type A hold-down, (b) Type B hold-down, and (c) Type C hold-down

As shown in Table 1, five replicates of each hold-down sub-type were tested under each monotonic and cyclic loading condition, except Type B-“P1”-ø4×60 and Type C sub-types which had three replicates tested under each loading type. For the monotonic tests, the displacement controlled loading rate of 2-3 mm/min was implemented. For the cyclic tests, the CUREE protocol proposed by Krawinkler et al. (2000) was implemented. Excursions of positive displacements were applied to the hold-down specimens to simulate the seismic excitations, as shown in Figure 4. The amplitudes of the loading cycles were determined based on the displacements that correspond to the post-peak loads equivalent to 80% of the peak loads obtained from the monotonic tests. The cyclic loads were applied at a constant rate of 10 mm/min.

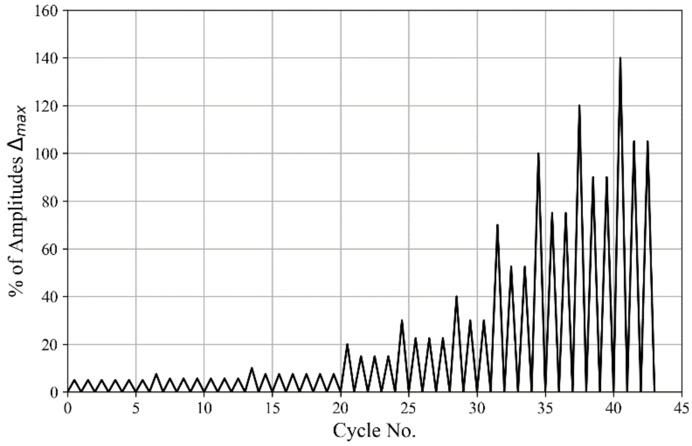


Figure 4 Cyclic loading protocol

3. Results and Discussions

3.1 Failure Modes

The dominant failure mode of the Type A hold-down connections with the full nailing pattern “F” was the hold-down bracket fracture, as shown in Figure 5a. The tensile fracture of the brackets generally occurred at their top nail rows which were responsible for carrying higher loads than other rows of nails. Also due to the loading eccentricity, the brackets were deformed out-of-plane as shown in Figure 5b. The combination of high tensile stresses and bending stresses at the reduced cross sections of the brackets ultimately led to the fracture failure. These observations suggest that such a failure mode can reduce the connection ductilty and energy dissipation, while it suppresses the ductile behaviour of the nails.

The Type A and Type B hold-down connections with the partial nailing patterns failed due to nail withdrawal and nail head shear-off (shown in Figure 6a) with bracket bending (shown in Figure 6b). As the number of nails was reduced by half from the full nailing pattern, the hold-down connection performance was governed by the structural behaviour of nails. In general, ductile nail behaviour characterized by severe bending of its shank and wood embedment crushing was observed, which eventually led to nail withdrawal failure. Interestingly, under the monotonic loading, nail head shear-off occured in a large number of nails in combination with the withdrawal failure. However, it was not typcially observed for the same connections under cyclic loading. A possible explanation for this phenomenon is that the cylic loading can gradually withdraw the nails and the locations of plastic hinges along the nail shanks may slightly shift during the cyclic tests.

In Type C hold-down connections with wide nail spacing, typical failure modes were nail head shear-off (shown in Figure 7a) and wood embedment crushing (shown in Figure 7b) because the 10 mm thick steel plates were sufficently strong and stiff. The nail behavior governed the connection performance. Since the nail size was ø4x100 and the nail embedment length was sufficent, it was not easy to facilitate nail withdrawal under both monotonic and cyclic loading. Therefore, nail head shear-off dominated the failure mode after the nails were significantly bent. Type C hold-down connections with narrow nail spacing typically failed due to the yielding of the nails (Figure 8a) and group tear-out (Figure 8b). As the nail spacing was decreased, wood shear failure along the loading direction was triggered. Such a failure mode could also affect the connection ductility and energy dissipation.

(a) (b)

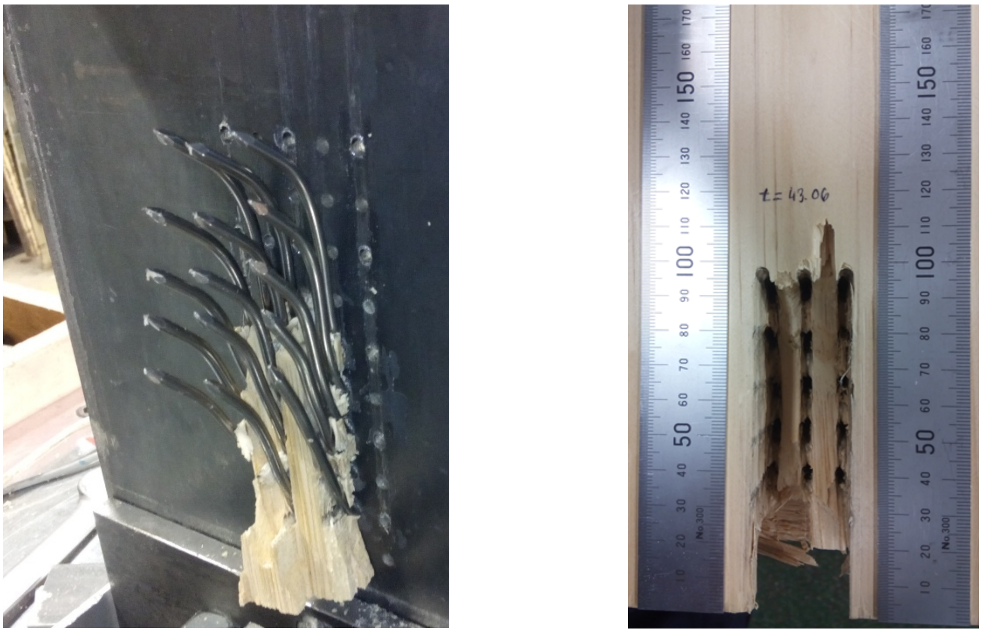
Figure 5 Typical failure modes in Type A hold-down connections with full nailing pattern “F”: (a) Bracket fracture, and (b) Bracket bending deformation

(a) (b)

Figure 6 Typical failure modes in Type A and Type B hold-down connections with partial nailing patterns: (a) Nail withdrawal and head shear-off, and (b) Bracket bending deformation

(a) (b)

Figure 7 Typical failure modes in Type C hold-down connections with wide nail spacing: (a) Nail head shear-off, and (b) Wood embedment crushing



(a) (b)

Figure 8 Typical failure modes in Type C hold-down connections with tight nail spacing: (a) Nail bending yielding, and (b) Group tear-out

3.2 Connection properties

The performance of the majority of the hold-down connections was governed by the nailed connections except Type A hold-down connections with the full nailing pattern in which the load-carry capacity was limited by the tensile fracture failure of the WHT440 brackets, as discussed in the earlier section. As an example, Figure 9 shows the monotonic and cyclic load-slip curves of all specimens in Type A-“F”-ø4x60. It was found that the curves in each hold-down sub-type were consistent. Therefore, for each hold-down sub-type, one representative monotonic load-slip curve and one representative cyclic load-slip curve are provided in Figures 10 to 12. In general, the backbones of the cyclic curves matched well against the monotonic curves.

Tables 4 to 6 list the derived connection properties based on the load-slip curves following the EEEP approach in ASTM E2126 (2011). The variability in each sub-type was primarily due to the inherent variability of wood including inconsistent density, moisture contents, grain direction, natural defects, etc. In terms of that, test results within 10% difference are considered to be similar on the following analysis.

The hold-down strength predictions followed Eurocode 5 (2004) except for Type A-“F”-ø4x60 hold-down connections as the governing failure mode was the steel bracket failure. Although 3 mm thick WHT440 bracket was between thin and thick plates compared with the nail diameter 4 mm, the condition of thick plate was satisfied due to the use of the conical-shaped cap, annular-ringed shank nails (Izzi et al. 2016). Equation (3) from Eurocode 5 was used to calculate the load-carrying capacities for the hold-downs when nail failure governed their failure mode. Equation (3) considers three possible failure modes: failure solely by embedment in the timber; failure by a combination of embedment in the timber and single yielding in the fastener; and failure by a combination of embedment in the timber and double yielding in the fastener. Equation (4) from the CLT Handbook was used to estimate the CLT embedment strength. For Type A-"F"-ø4x60 hold-down connections, the manufacturer specified bracket tensile strength was provide as the predicted hold-down strength.

$$F_k = \min \begin{cases} n_1 n_2 f_{h,k} t_1 d \\ n_1 n_2 f_{h,k} t_1 d \left[\sqrt{2 + \dfrac{4 M_{y,Rk}}{f_{h.k} d t_1^2}} - 1 \right] + \dfrac{F_{ax.Rk}}{4} \\ n_1 n_2 2.3 \sqrt{2 M_{y,Rk} f_{h.k} d} + \dfrac{F_{ax.Rk}}{4} \end{cases} \tag{3}$$

$$f_{h,k} = 0.112 d^{-0.5} \rho_k^{1.05} \tag{4}$$

Where, F_k = characteristic value of hold-down strength; n_1, n_2 = the row and column number of nails in the hold-down connection; $f_{h,k}$ = the characteristic embedment strength in the timber member; t_1 = the nail penetration depth; d = the nail diameter; $M_{y,Rk}$ = the characteristic nail yield moment (6500 N·mm for ø4x50 and ø4x60 according to manufacturer information and 8822 N·mm for ø4x100 according to bending test); $F_{ax,Rk}$ = the characteristic withdrawal capacity of nails calculated according to Eurocode 5; ρ_k = the characteristic density of timber.

To calculate the fastener group characteristic strength, the actual fastener quantity was used instead of the effective fastener number n_{eff} provided in Eurocode 5, as recommended by previous research from Ottenhaus et al. (2018b).

The overstrength factors of individual hold-down connections $\gamma_{Rd,i}$ and the hold-down group γ_{Rd} were calculated by Equation (5) and Equation (6), respectively. Equation (6) was derived from Equation (2) assuming that the γ_M is 1.0 according to Eurocode 8 (2004). $F_{0.95}$ for each hold-down group was calculated according to EN 14358 assuming the data were normally distributed.

$$\gamma_{Rd,i} = \frac{F_y}{F_k} \tag{5}$$

$$\gamma_{Rd} = \frac{F_{0.95}}{F_k} \quad (6)$$

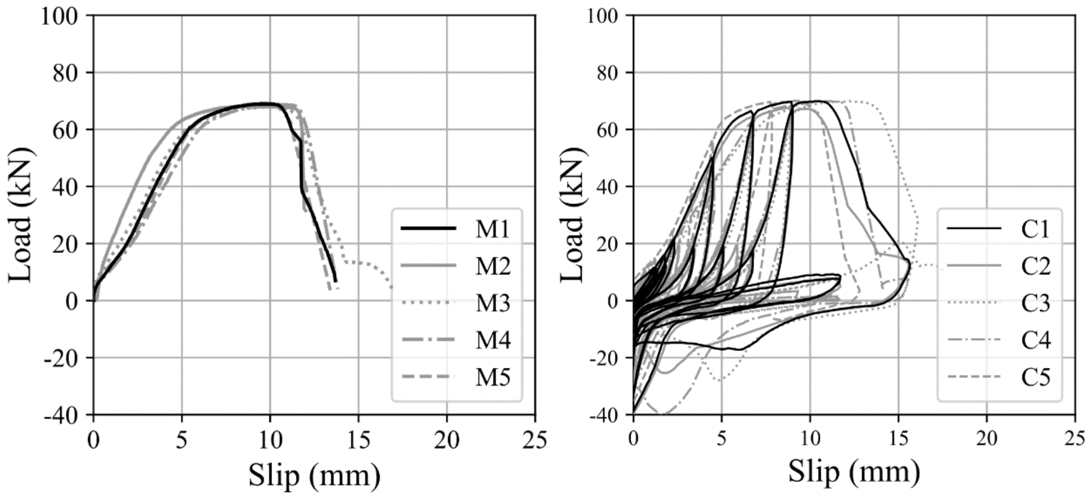


Figure 9 Monotonic and cyclic load-slip curves of Type A-“F”-ø4x60

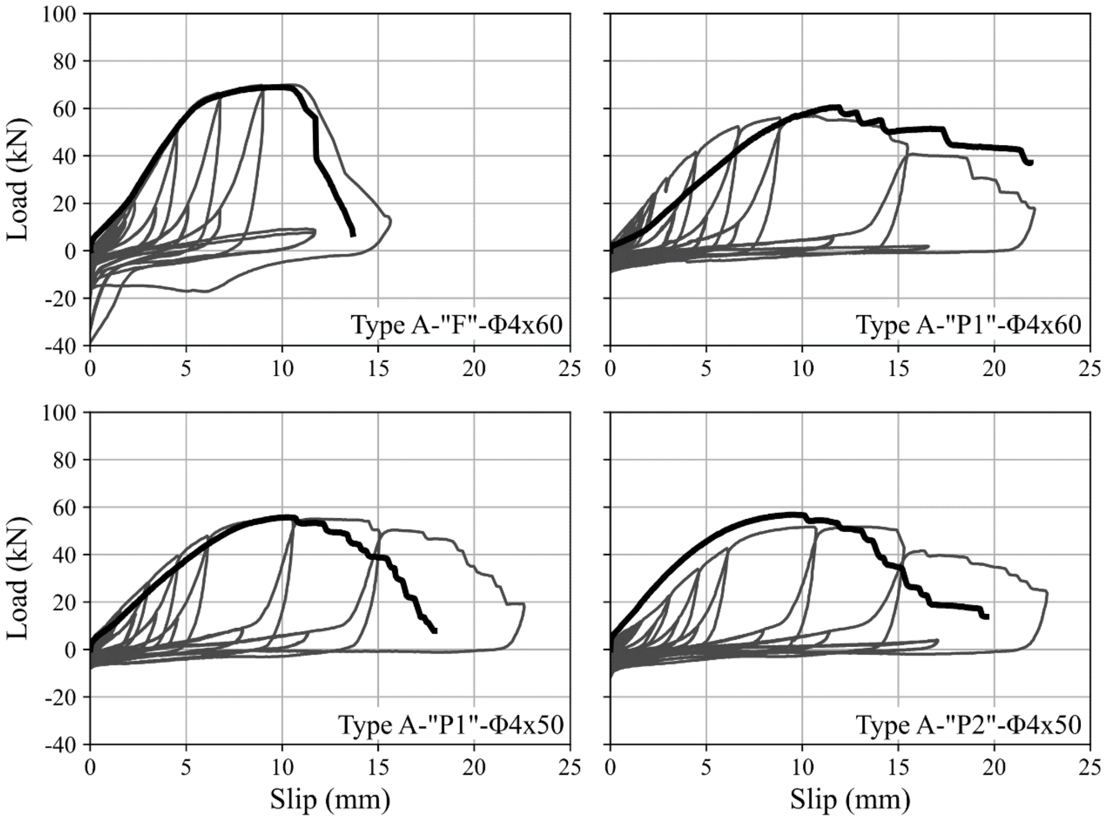


Figure 10 Load-slip curves of Type A hold-down connections

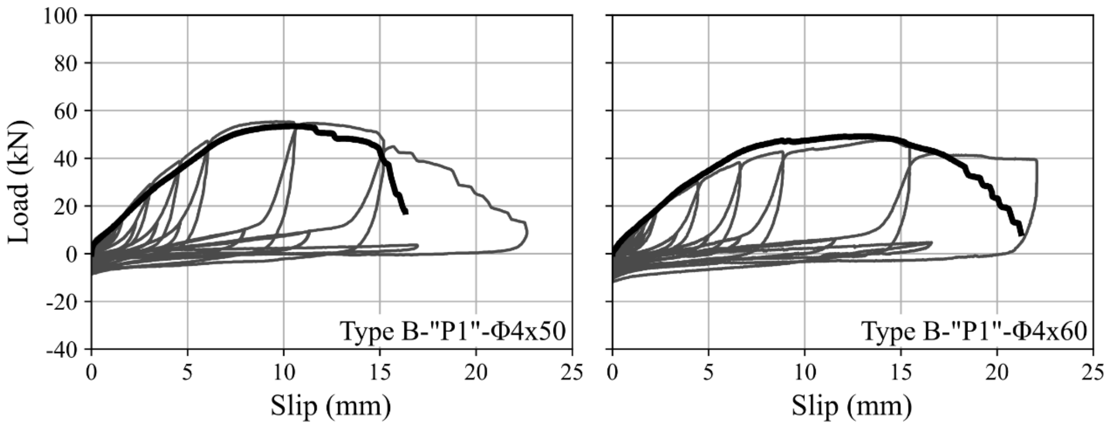


Figure 11 Load-slip curves of Type B hold-down connections

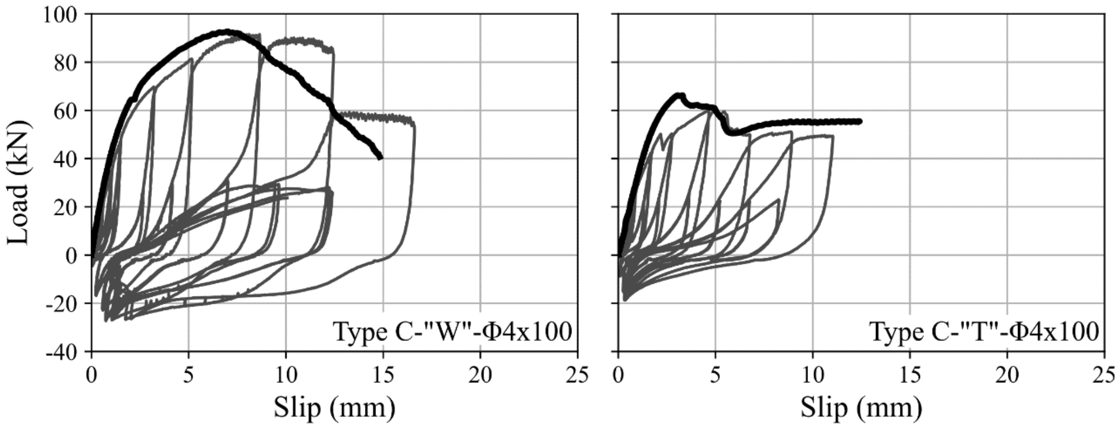


Figure 12 Load-slip curves of Type C hold-down connections

Table 4 Summary of Type A hold-down connections

Hold-down sub-type		$F_{k.}$[1] (kN)	F_y (kN)	Δ_y (mm)	F_{max} (kN)	Δ_{max} (mm)	F_u (kN)	Δ_u (mm)	K (kN/mm)	μ	$\gamma_{Rd,i}$	γ_{Rd}
	M1		65.0	4.6	68.2	8.7	54.5	12.4	13.5	2.6		
	M2		65.7	5.2	68.1	9.8	54.4	12.1	12.6	2.3		
	M3		67.7	6.2	69.0	10.1	55.2	11.7	11.0	1.9		
	M4		70.0	7.4	68.8	10.5	55.1	12.3	9.5	1.7		
	M5		70.4	6.9	69.2	9.8	55.4	11.4	10.2	1.7		
Type A-“F”-ø4x60	*M_{avg}*	63.4[1]	*67.8*	*6.1*	*68.7*	*9.8*	*54.9*	*11.9*	*11.4*	*2.0*	n/a	n/a
	C1		71.2	7.1	69.2	10.6	55.9	12.1	10.0	1.7		
	C2		68.5	7.1	67.5	8.9	54.0	11.3	9.7	1.6		
	C3		68.4	8.1	69.9	12.3	55.9	14.6	8.5	1.8		
	C4		69.5	7.7	68.8	11.2	55.9	12.5	9.0	1.6		
	C5		71.8	6.4	70.0	9.3	56.0	10.9	11.2	1.7		
	C_{avg}		*69.9*	*7.3*	*69.1*	*10.4*	*55.5*	*12.3*	*9.7*	*1.7*		

	Avg-All		**68.8**	**6.6**	**68.9**	**10.1**	**55.2**	**12.1**	**10.6**	**1.9**		
Type A-"P1"-ø4x60	M1	37.8	53.8	8.5	58.1	16.7	46.5	18.9	6.4	2.2	1.42	**1.62**
	M2		55.3	9.0	60.5	11.9	48.4	17.4	6.1	1.9	1.46	
	M3		55.0	10.3	59.5	17.2	47.6	25.1	5.3	2.4	1.45	
	M4		55.6	11.8	59.5	19.8	47.6	29.5	4.7	2.5	1.47	
	M5		50.5	8.8	54.2	16.0	43.4	22.4	5.8	2.5	1.34	
	M_{avg}		*54.0*	*9.7*	*58.4*	*16.3*	*46.7*	*22.7*	*5.7*	*2.3*		
	C1		57.6	7.0	62.6	15.5	50.1	18.2	8.2	2.6	1.52	
	C2		52.3	4.9	56.7	10.7	45.4	15.3	10.6	3.1	1.38	
	C3		56.8	6.4	61.8	14.9	49.4	20.8	8.9	3.3	1.50	
	C4		49.7	4.9	55.4	12.8	44.3	22.0	10.1	4.4	1.31	
	C5		45.2	4.1	49.7	8.9	39.7	21.4	10.9	5.1	1.20	
	C_{avg}		*52.3*	*5.5*	*57.2*	*12.6*	*45.8*	*19.5*	*9.7*	*3.7*		
	Avg-All		**53.2**	**7.6**	**57.8**	**14.5**	**46.2**	**21.1**	**7.7**	**3.0**		
Type A-"P1"-ø4x50	M1	36.7	42.6	5.5	45.4	10.4	36.3	18.4	7.7	3.3	1.16	**1.61**
	M2		51.4	6.3	55.8	10.3	44.6	13.7	8.1	2.2	1.40	
	M3		46.9	4.2	51.2	11.7	41.0	15.7	11.2	3.8	1.28	
	M4		52.1	7.0	55.9	12.0	44.7	15.5	7.5	2.2	1.42	
	M5		56.6	7.8	58.7	9.6	46.9	13.2	7.3	1.7	1.54	
	M_{avg}		*49.9*	*6.2*	*53.4*	*10.8*	*42.7*	*15.3*	*8.4*	*2.6*		
	C1		52.8	3.9	57.6	11.6	46.1	15.7	13.6	4.0	1.44	
	C2		51.0	5.1	55.1	10.5	44.1	19.0	10.1	3.8	1.39	
	C3		54.4	4.6	58.7	10.1	46.9	14.3	11.9	3.1	1.48	
	C4		49.8	5.1	54.1	15.0	43.3	19.8	9.8	3.9	1.36	
	C5		49.0	5.4	53.8	10.1	43.1	16.2	9.0	3.0	1.34	
	C_{avg}		*51.4*	*4.8*	*55.9*	*11.5*	*44.7*	*17.0*	*10.9*	*3.6*		
	Avg-All		**50.7**	**5.5**	**54.6**	**11.1**	**43.7**	**16.1**	**9.6**	**3.1**		
Type A-"P2"-ø4x50	M1	36.7	46.4	5.2	49.7	12.4	39.7	16.6	8.9	3.2	1.26	**1.58**
	M2		52.7	6.8	58.8	11.6	47.0	15.0	7.7	2.2	1.44	
	M3		49.5	5.2	52.8	11.1	42.2	16.4	9.4	3.1	1.35	
	M4		51.8	4.4	56.8	9.6	45.5	13.7	11.9	3.1	1.41	
	M5		57.2	5.0	61.0	10.0	48.8	13.0	11.5	2.6	1.56	
	M_{avg}		*51.5*	*5.3*	*55.8*	*10.9*	*44.6*	*14.9*	*9.9*	*2.8*		
	C1		45.1	6.1	48.4	12.6	38.7	21.8	7.4	3.6	1.23	
	C2		54.2	7.9	58.9	12.7	47.1	16.4	6.8	2.1	1.48	
	C3		49.5	6.8	51.6	13.6	41.3	16.4	7.2	2.4	1.35	
	C4		48.0	8.8	50.2	17.4	40.2	20.7	5.4	2.3	1.31	
	C5		50.2	8.7	53.2	15.1	42.6	19.6	5.8	2.3	1.37	
	C_{avg}		*49.4*	*7.7*	*52.5*	*14.3*	*42.0*	*19.0*	*6.5*	*2.5*		
	Avg-All		**50.5**	**6.5**	**54.1**	**12.6**	**43.3**	**17.0**	**8.2**	**2.7**		

Note: 1. the hold-down strength prediction of Type A-“F”-ø4x60 is governed by hold-down bracket tensile capacity. Other Type A hold-down strength predictions are governed by nail strength.

Table 4 summarizes the connection performance parameters of the four Type A hold-down sub-types. The average yield strength of Type A-“F”-ø4x60 was 68.8 kN, similar with the characteristic strength 63.4 kN of the WH440 bracket listed in the product specifications (Rothoblaas, 2019). Due to the brittle tensile failure of the bracket, the average ductility factor (μ) of 1.9 was achieved. Therefore, this hold-down system with full nailing pattern may not be ideal to be used as a ductile element in CLT shear wall design, and its overstrength factor is not provided in the table. In Type A-“P1”-ø4x60 hold-down connections, the nail quantity was reduced by half from the full nailing pattern. This change in the nailing pattern increased the connections’ average ductility factor by 58% to 3.0, while it dropped the average yield strength by 23% from 68.8 kN to 53.2 kN. In Type A-“P1”-ø4x50 hold-down connections, the connection configuration was the same as the Type A-“P1”-ø4x60 except that the nails were 10 mm shorter. The yield strength and the average μ of both hold-down types were similar (53.2 kN vs. 50.7 kN and 3.0 vs. 3.1). Type A-“P2”-ø4x50 hold-down connections had the same number of nails as Type A-“P1”-ø4x50, but the nail spacing was reduced by half and the nailing pattern was staggered, as shown Figure 1. The change of the nailing pattern did not have an influence on the yield strength (50.5 kN vs. 50.7 kN), but reduced μ by 13% from 3.1 to 2.7. The overstrength factors γ_{Rd} of the Type A hold-down connections with partial nailing patterns ranged from 1.58 to 1.62 with an average of 1.60, which was consistent with the range of overstrength factors of dowelled CLT hold-down connections derived by Ottenhaus et al. (2018b).

Table 5 summarizes the connection performance parameters of the two Type B hold-down sub-types. In Type B-“P1”-ø4x50 hold-down connections, the connection configuration was the same as Type A-“P1”-ø4x50 hold-down connections except the RP CLT was used instead of DF CLT. This change in wood species did not significantly affect the average μ and yield strength (2.9 vs. 3.1 and 49.6 kN vs. 50.7 kN). Comparing the results of Type A-“P1”-ø4x60 sub-type and Type B-“P1”-ø4x60 sub-type, with the same connection configuration, the average yield strength of the RP CLT specimens was 16% lower than that of the DF CLT specimens (44.5 kN vs. 53.2 kN). However, the average ductility μ of the RP CLT specimens was 43% higher than that of the DF CLT specimens (4.3 vs. 3.0). The overstrength factors γ_{Rd} of the Type B hold-down connection sub-types were 1.45 and 1.57, respectively, with an average of 1.51, similar with the overstrength factors of the Type A hold-down connections with partial nailing patterns. These experimental results indicated that the effect of species on the connection performance became more evident as the nail length was increased. Considering that these two wood species had similar density, their other inherent features such as grain tightness and natural defects possibly led to the reported discrepancy in the yield strength and ductility. More work is recommended to investigate such a phenomenon further.

Table 5 Summary of Type B connections

Hold-down sub-type		**$F_{k.}$ (kN)**	**F_y (kN)**	**Δ_y (mm)**	**F_{max} (kN)**	**Δ_{max} (mm)**	**F_u (kN)**	**Δ_u (mm)**	**K (kN/mm)**	**μ**	**$\gamma_{Rd,i}$**	**γ_{Rd}**
Type B-“P1”-ø4x50	M1	37.2	49.6	5.1	53.7	9.7	43.0	15.1	9.7	2.9	1.33	**1.57**
	M2		52.8	4.6	58.0	9.3	46.4	12.4	11.5	2.7	1.42	
	M3		51.5	6.7	54.0	11.5	43.2	14.1	7.6	2.1	1.38	
	M4		45.6	5.5	47.8	11.6	38.3	15.8	8.2	2.9	1.23	
	M5		49.0	5.5	53.5	11.1	42.8	15.0	8.9	2.7	1.32	
	M_{avg}		*49.7*	*5.5*	*53.4*	*10.6*	*42.7*	*14.5*	*9.2*	*2.7*		
	C1		53.4	6.1	57.2	10.4	45.8	17.0	8.8	2.8	1.44	
	C2		52.4	7.2	55.4	12.6	44.3	15.9	7.3	2.2	1.41	
	C3		39.3	3.9	43.0	10.6	34.4	19.1	10.2	4.9	1.06	
	C4		51.3	5.2	55.4	9.6	44.3	15.8	9.9	3.0	1.38	
	C5		51.1	5.0	55.5	10.3	44.4	15.7	10.3	3.2	1.37	
	C_{avg}		*49.5*	*5.5*	*53.3*	*10.7*	*42.7*	*16.7*	*9.3*	*3.2*		
	Avg-All		**49.6**	**5.5**	**53.4**	**10.7**	**42.7**	**15.6**	**9.2**	**2.9**		
Type B-“P1”-ø4x60	M1	38.3	48.8	4.5	52.7	12.4	42.1	16.9	10.9	3.8	1.27	**1.45**
	M2		45.5	5.7	49.2	13.5	39.3	17.7	8.0	3.1	1.19	
	M3		37.0	4.1	40.4	13.8	32.3	17.6	8.9	4.3	0.97	
	M_{avg}		*43.8*	*4.8*	*47.4*	*13.2*	*37.9*	*17.4*	*9.3*	*3.7*		
	C1		43.9	3.8	50.2	14.5	40.2	20.9	11.5	5.5	1.15	
	C2		49.8	5.5	54.6	14.4	43.7	25.2	9.1	4.6	1.30	
	C3		41.7	5.3	47.6	13.9	38.1	22.1	7.9	4.2	1.09	
	C_{avg}		*45.1*	*4.9*	*50.8*	*14.3*	*40.7*	*22.7*	*9.5*	*4.8*		
	Avg-All		**44.5**	**4.8**	**49.1**	**13.8**	**39.3**	**20.1**	**9.4**	**4.3**		

Table 6 summarizes the connection performance parameters of the two Type C hold-down sub-types. Compared with the results of Type B hold-down connections composed of the same CLT species (RP) and the same nail quantities, Type C hold-down configurations had significantly higher load-carrying capacity and ductility. Type

C-“W”-ø4x100 hold-down configuration achieved the average yield strength of 81.4 kN, which was 64% higher than the largest average yield strength of Type B connections (49.6kN). Besides, the average μ increased to 6.3, which was 47% higher than the largest average μ=4.3 of Type B connections. The overstrength factor γ_{Rd}=2.04 was significantly larger than all the other hold-down connection sub-types. In Type C-“T”-ø4x100 connections, nail spacing within and between the rows was reduced by half when compared with Type C-“W”-ø4x100 connections. The reduced nail spacing triggered group tear-out failure that compromised the ductile behaviour of the nails. As a consequence, the average yield strength decreased by 31%, from 81.4 kN to 55.8 kN, and the average μ decreased by 25%, from 6.3 to 4.7. Nonetheless, Type C-“T”-ø4x100 connections still outperformed all Type B connections on both yield strength and ductility factors.

Table 6 Summary of Type C hold-down results

Hold-down sub-type	**Specimen**	**F_k (kN)**	**F_y (kN)**	**Δ_y (mm)**	**F_{max} (kN)**	**Δ_{max} (mm)**	**F_u (kN)**	**Δ_u (mm)**	**K (kN/mm)**	**μ**	**$\gamma_{Rd,i}$**	**γ_{Rd}**
Type C-“W”-ø4x100	M1	43.4	77.6	2.0	87.7	8.2	70.1	15.2	39.1	7.5	1.79	**2.04**
	M2		85.1	2.0	94.8	7.5	75.8	11.8	43.0	6.0	1.96	
	M3		82.3	1.9	92.7	7.0	74.2	10.6	43.6	5.6	1.90	
	M_{avg}		*81.7*	*1.9*	*91.7*	*7.6*	*73.4*	*12.6*	*41.9*	*6.4*		
	C1		82.3	2.5	92.1	9.8	73.7	15.4	33.2	6.2	1.90	
	C2		83.5	2.4	91.5	8.1	73.2	12.5	34.2	5.1	1.92	
	C3		77.6	1.8	86.1	8.4	68.9	12.7	44.1	7.2	1.79	
	Avg-C		*81.1*	*2.2*	*89.9*	*8.8*	*71.9*	*13.5*	*37.2*	*6.2*		
	Avg-All		**81.4**	**2.1**	**90.8**	**8.2**	**72.7**	**13.0**	**39.6**	**6.3**		
Type C-“T”-ø4x100	M1	43.4	60.4	1.8	66.2	3.3	53.0	5.5	33.7	3.1	1.39	**1.59**
	M2		55.3	2.1	64.3	4.8	51.4	5.5	26.7	2.7	1.27	
	M3		62.3	1.9	71.3	4.7	57.0	16.5	32.9	8.7	1.44	
	M_{avg}		*59.3*	*1.9*	*67.3*	*4.3*	*53.8*	*9.2*	*31.1*	*4.8*		
	C1		58.1	2.4	66.6	10.5	53.3	12.9	23.9	5.3	1.34	
	C2		47.5	2.2	54.0	3.9	43.2	4.7	21.8	2.1	1.10	
	C3		51.1	1.7	60.3	5.1	48.3	11.0	30.6	6.6	1.18	
	Avg-C		*52.2*	*2.1*	*60.3*	*6.5*	*48.3*	*9.5*	*25.4*	*4.7*		
	Avg-All		**55.8**	**2.0**	**63.8**	**5.4**	**51.0**	**9.3**	**28.3**	**4.7**		

The results of yield strength and ductility from the monotonic tests and cyclic tests were also compared for all hold-down connection sub-types except Type A-“F”-ø4x60 what experienced brittle bracket fracture failure. All hold-down connection sub-types other than Type C-“T”-ø4x100 achieved the similar average yield strength values during the monotonic and cyclic tests. However, the connection sub-types composed of WHT440 brackets, except Type A-“P2”-ø4x50, achieved larger average ductility factors during the cyclic tests than the monotonic tests by a range of 16% to 38%. When the 10 mm thick steel plates were used, the results in the average ductility factors obtained under the two loading types were similar.

4. CONCLUSIONS

An experimental study was conducted to investigate the structural performance of nailed CLT hold-down connections for CLT shear walls. Hold-down connection properties including strength, stiffness, ductility and overstrength were derived. The influence of various design parameters on the hold-down behaviour was also studied. The main conclusions are provided as follows:

- The commercial WHT440 hold-down brackets with 15 ø4x50 or ø4x60 nails in the partial nailing patterns were able to provide connection ductility factors of μ=2.7-4.3 and connection overstrength factors of γ_{Rd} = 1.45-1.62. However, it is critical to avoid brittle tensile failure of the bracket which may cause low ductility of μ<2.0. The initial stiffness of hold-down connections with partial nailing patterns ranged from 7.7-9.6 kN/mm.
- The hold-down connections with 10 mm thick steel brackets and 15 ø4x100 nails had much higher ductility factors of μ=4.7-6.3, although the tight nailing pattern caused failure mode cross-over to group tear out. An overstrength factor of γ_{Rd} = 1.59 was derived for the tight nailing pattern and γ_{Rd} = 2.04 for the wide nailing pattern. The average initial stiffness ranged from 28.3-39.6 kN/mm, much stiffer than the commercial hold-down connections tested in this study.
- In general, two nail lengths (ø4x50 vs. ø4x60) caused similar yield strength and ductility for the hold-down connections. For the hold-down connections with DF CLT, partial nailing patterns “P1” and “P2” had similar yield strength and overstrength γ_{Rd} but the ductility of “P2” was reduced by 13% when compared to that of “P1”.

- The test results of DF CLT and RP CLT indicated that the effect of species on the connection performance became more evident as the nail length was increased. More research is recommended to investigate the influence of timber species further.
- Except for Type C-“T”-ø4x100, the hold-down average yield strength obtained from the monotonic tests was similar to the one obtained from cyclic tests. For Type C hold-down connections, the ductility from the monotonic tests was similar to the one obtained from cyclic tests as well. However, for Type A and B hold-down connections, the average cyclic ductility was higher than the monotonic ductility by a range of 16% to 38% except Type A-“P2”-ø4x50.

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REFERENCES

- AS/NZS 4671:2001, 2001. Steel Reinforcing Materials. Standards New Zealand, Wellington, New Zealand
- NZS/AS 1720.1, 2019. Timber Structures Part 1: Design methods (draft for public consultation). Standards New Zealand, Wellington, New Zealand
- ASTM E2126, 2011. Standard Test Methods for Cyclic (Reversed) Load Test for Shear Resistance of Vertical Elements of the Lateral Force Resisting Systems for Buildings, ASTM International.
- Benedetti, F., Rosales, V., Opazo-Vega, A., Norambuena-Contreras, J. and Jara-Cisterna, A., 2019. Experimental and numerical evaluation of hold-down connections on radiata pine Cross-Laminated-Timber shear walls: a case study in Chile. European Journal of Wood and Wood Products, 77(1): 79-92.
- Brühl, Frank, Jörg Schänzlin, and Ulrike Kuhlmann. 2014. Ductility in timber structures: Investigations on over-strength factors. Materials and Joints in Timber Structures. Springer, Dordrecht, Netherlands
- Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G. and Thiel, A., 2016. Cross laminated timber (CLT): overview and development. European Journal of Wood and Wood Products, 74(3): 331-351.
- Ceccotti, A., Sandhaas, C., Okabe, M., Yasumura, M., Minowa, C. and Kawai, N., 2013. SOFIE project–3D shaking table test on a seven-storey full-scale cross-laminated timber building. Earthquake Engineering and Structural Dynamics, 42(13): 2003-2021.
- European Standard Eurocode 5, 2004 Design of timber structures—part 1-1: general-common rules and rules for buildings/incl Amendment A1. European Committee for Standardization, Bruxelles, Belgium.
- European Standard Eurocode 8, 2004. Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings". European Committee for Standardization, Bruxelles, Belgium.
- EN 14358, 2016. Timber structures –Calculation and verification of characteristic values. European Committee for Standardization, Bruxelles, Belgium.
- Flatscher, G., Bratulic, K. and Schickhofer, G., 2015. Experimental tests on cross-laminated timber joints and walls. Proceedings of the Institution of Civil Engineers-Structures and Buildings, 168(11):868-877.
- Gavric, I., Fragiacomo, M. and Ceccotti, A., 2015a. Cyclic behavior of typical screwed connections for cross-laminated (CLT) structures. European Journal of Wood and Wood Products, 73(2):179-191.
- Gavric, I., Fragiacomo, M. and Ceccotti, A., 2015b. Cyclic behaviour of typical metal connectors for cross-laminated (CLT) structures. Materials and Structures, 48(6):1841-1857.
- Hossain, A., Danzig, I. and Tannert, T., 2016. Cross-laminated timber shear connections with double-angled self-tapping screw assemblies. ASCE Journal of Structural Engineering, 142(11):04016099.
- Izzi, M., Flatscher, G., Fragiacomo, M., & Schickhofer, G, 2016. Experimental investigations and design provisions of steel-to-timber joints with annular-ringed shank nails for Cross-Laminated Timber structures. Construction and Building Materials, 122, 446–457.

- Jorissen, A. and Fragiacomo, M., 2011. General notes on ductility in timber structures. Engineering structures, 33(11): 2987-2997.
- Karacabeyli, E. and Douglas, B., 2013. CLT handbook. US Edition, FPInnovations and Binational Softwood Lumber Council, Point-Claire, Quebec, Canada
- Krawinkler, Parisi, F., Ibarra, L., Ayoub, A., and Medina, R. 2000. Development of a Testing Protocol for Wood Frame Structures. *CUREE Publication No. W-02*, Consortium of Universities for Research in Earthquake Engineering, CA, U.S.
- Li M. and Lam F. 2009. Lateral performance of non-symmetric diagonal-braced wood shear walls. ASCE Journal of Structural Engineering 135(2): 178-186.
- Li, M., Foschi, R. O. and Lam, F. 2012. Modeling hysteretic behaviour of panel-sheathed wood shear walls with a protocol-independent nail connection algorithm. ASCE Journal of Structural Engineering 138(1):99-108.
- Lim, H., Lam, F., Foschi, R. and Li, M. 2017. “Numerical modelling of nail connection performance of strand-based wood composites”. ASCE Journal of Engineering Mechanics. 143(6): 04017015.
- NZS 3603:1993 Timber Structures Standard, Standards New Zealand, Wellington, New Zealand, 1993.
- Ottenhaus, L., Li, M. and Smith T. 2018a. “Structural performance of large-scale dowelled CLT connections under monotonic and cyclic loading”, Engineering Structures 176:41-48.
- Ottenhaus, L., Li, M., Smith, T. and Quenneville, P. 2018b. “Overstrength of dowelled CLT connections under monotonic and cyclic loading”, Bulletin of Earthquake Engineering. 16(2):753-773.
- Polastri, A., Giongo, I. and Piazza, M., 2017. An innovative connection system for cross-laminated timber structures. Structural Engineering International, 27(4): 502-511.
- Pozza, L., Saetta, A., Savoia, M. and Talledo, D., 2017. Coupled axial-shear numerical model for CLT connections. Construction and Building Materials, 150: 568-582.
- Pozza, L., Saetta, A., Savoia, M. and Talledo, D., 2018. Angle bracket connections for CLT structures: Experimental characterization and numerical modelling. Construction and Building Materials, 191: 95-113.
- Rothoblaas, 2018, Threaded nail – Screw with cylindrical head for plates. Rothoblaas design manual, Cortaccia, Italy.
- Rothoblaas, 2019. WHT Angle bracket for tensile loads. Rothoblaas design manual. Cortaccia, Italy.
- Schneider, J., Karacabeyli, E., Popovski, M., Stiemer, S.F. and Tesfamariam, S., 2014. Damage assessment of connections used in cross-laminated timber subject to cyclic loads. Journal of Performance of Constructed Facilities, 28(6):4014008.
- Tomasi, R. and Smith, I., 2015. Experimental characterization of monotonic and cyclic loading responses of CLT panel-to-foundation angle bracket connections. ASCE Journal of Materials in Civil Engineering, 27(6):04014189.

Declaration of interests

 The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Minghao Li: Conceptualization, Funding acquisition, Project administration, Supervision, Writing – Original Draft, and Writing – Review & Editing.

Lisa-Mareike Ottenhaus: Conceptualization and Writing - Review & Editing.

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